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He II HEAT EXCHANGER TEST UNIT FOR THE LHC INNER TRIPLET

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US-LHC Accelerator Project
Brookhaven – Fermilab - Berkeley

Headlines

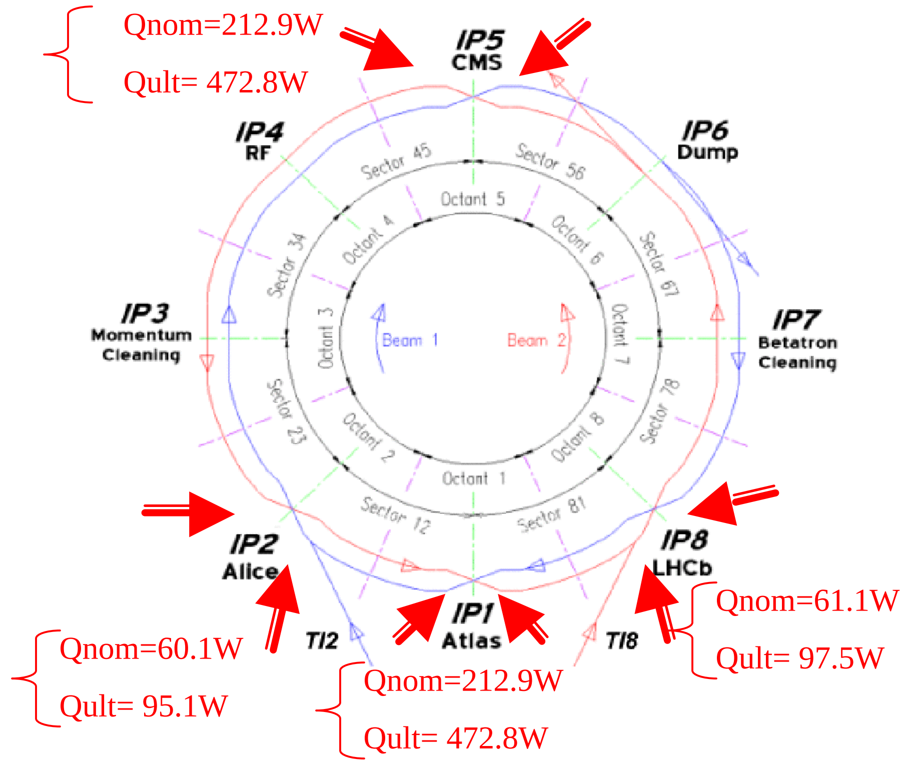
- Overview on the LHC IR inner triplet
- IT-HXTU test description and Purpose
- Thermal measurements under investigation
- Results and discussion
- Consequences on the inner triplet

Overview on the LHC IR inner triplet

Eight inner triplets located @ the Interaction Regions.

C-08C-03 LHC Interaction Region Quadrupole

Cryostat Design



Concerns:

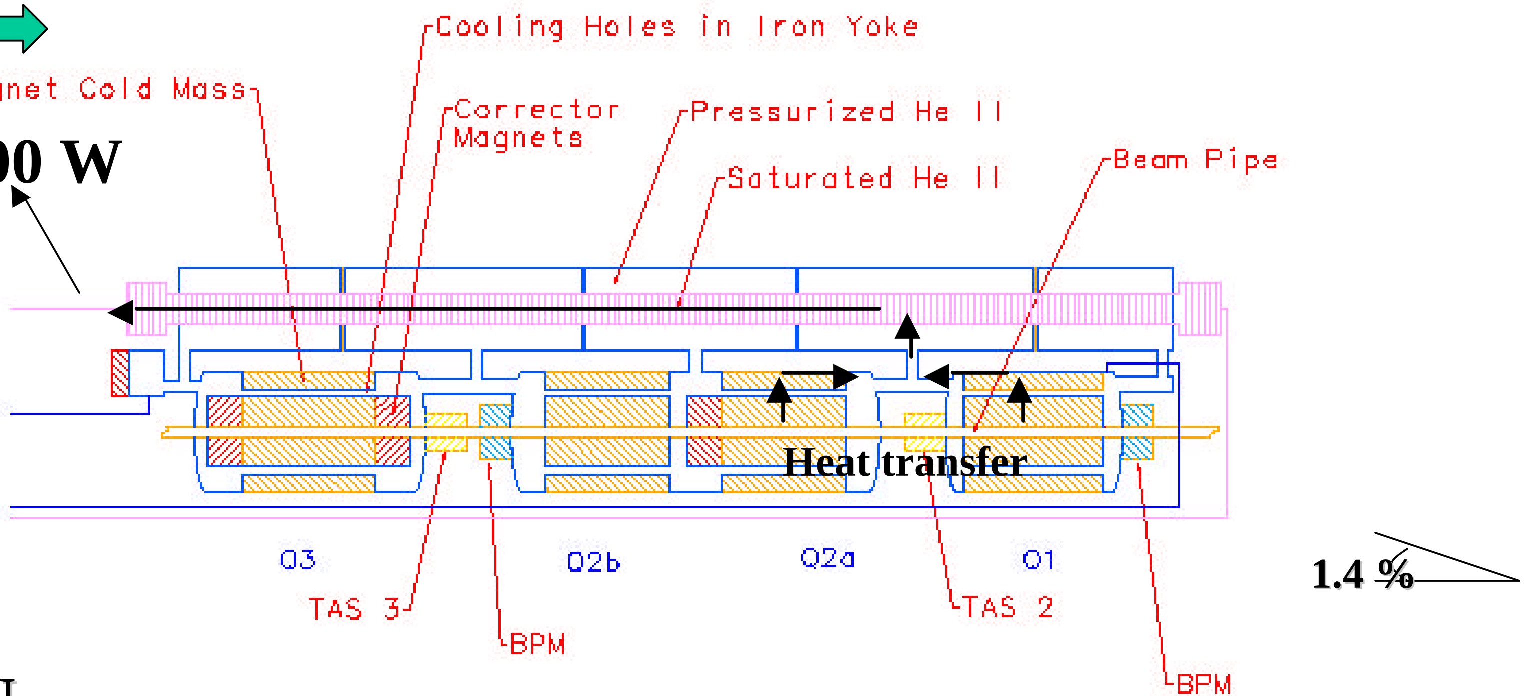
☞Large dynamic heat loads @ 1.9 K

☞Require a large Heat Exchanger tube

Inner triplet heat loads - estimated				
Temperature level	**50 to 75 K**	**4.6K**	**1.9K**	**Notes**
Static heat loads (W)	**220**	**0**	**18**	**1,2**
Dynamic heat loads (W)	**0**	**17**	**184**	**3**
Total heat loads (W)	**220**	**17**	**202**	

From the LHC IR inner triplet to the IT-HXTU

Inner triplet



IT-HXTU

- **Four similar modules (7 m x ø 0.8 m) to simulate the IT cooling scheme.**
  - **Magnet simulators (resistive heaters)**
  - **Full He II capacity (~800 l)**

Purpose of the IT-HXTU

- Validation of the the inner triplet cooling scheme by checking the max. temperature rise in the stagnant and pressurized He II.

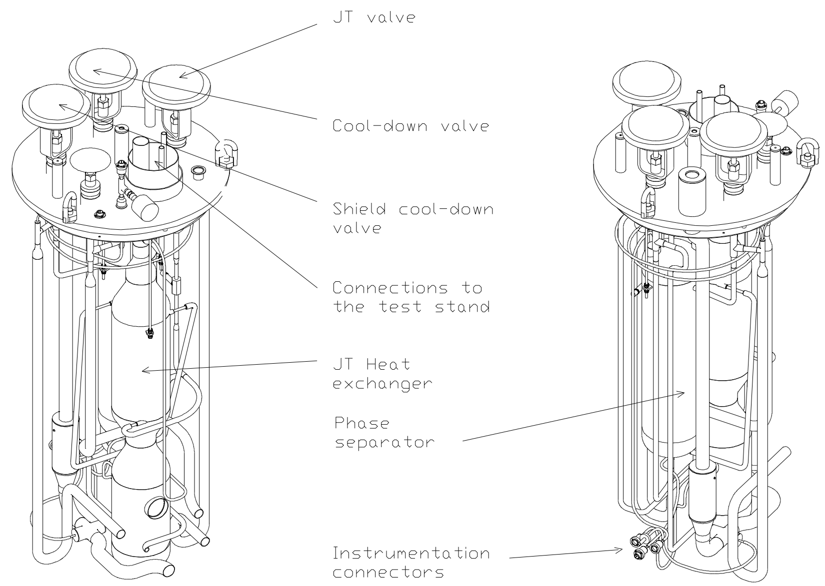
- Validation of theoretical estimation of the heat transfer in Pressurized He II.

- Measurement of the heat exchanger tube wetted area.

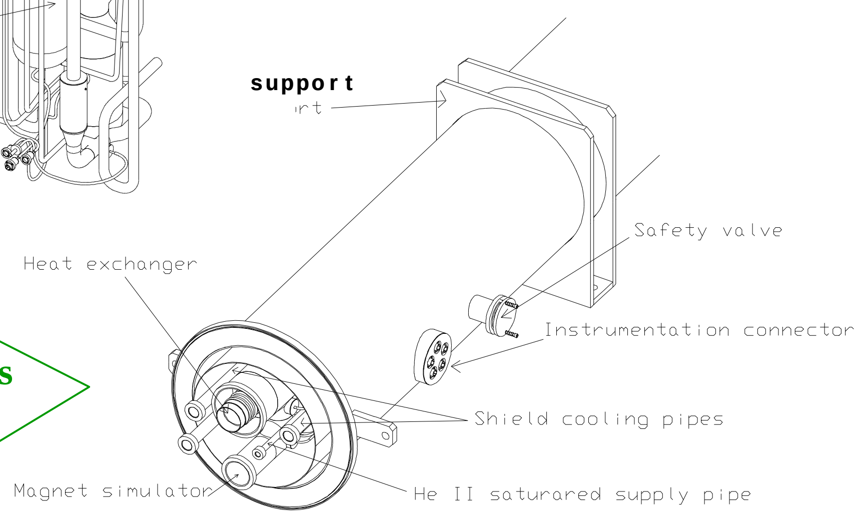
- Development of the Nonlinear Model-Based Predictive Control.

C-02B-03 Nonlinear Advanced Control of the LHC Inner Triplet Heat Exchanger Test Unit

View of the IT-HXTU

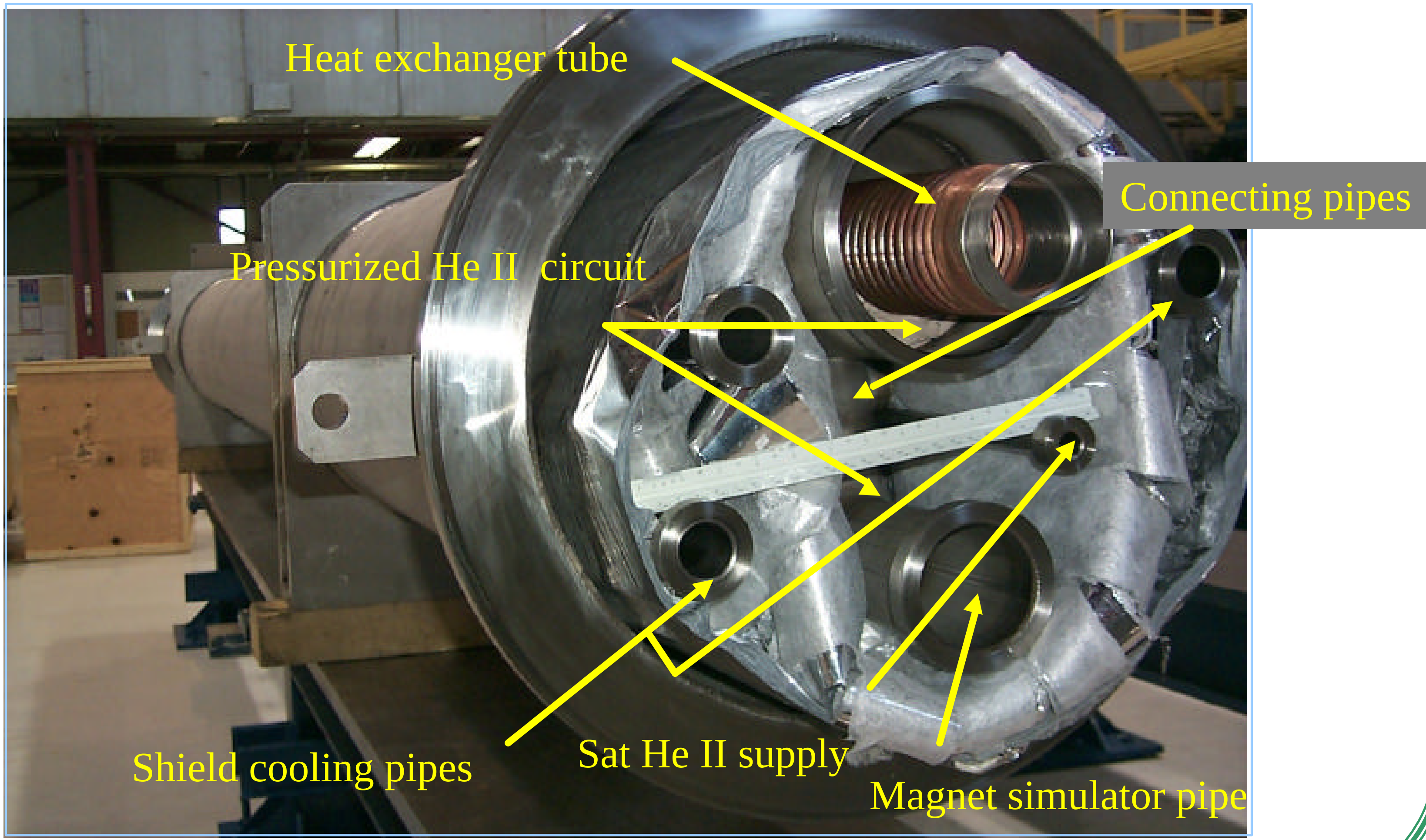


The feedbox without the thermal shield and vacuum vessel



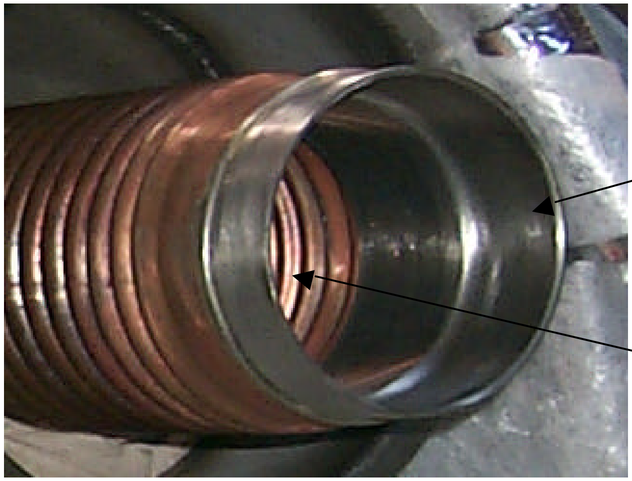
Side view of one of the four identical modules

View of the IT-HXTU



View of the IT-HXTU

The IT Heat Exchanger tube



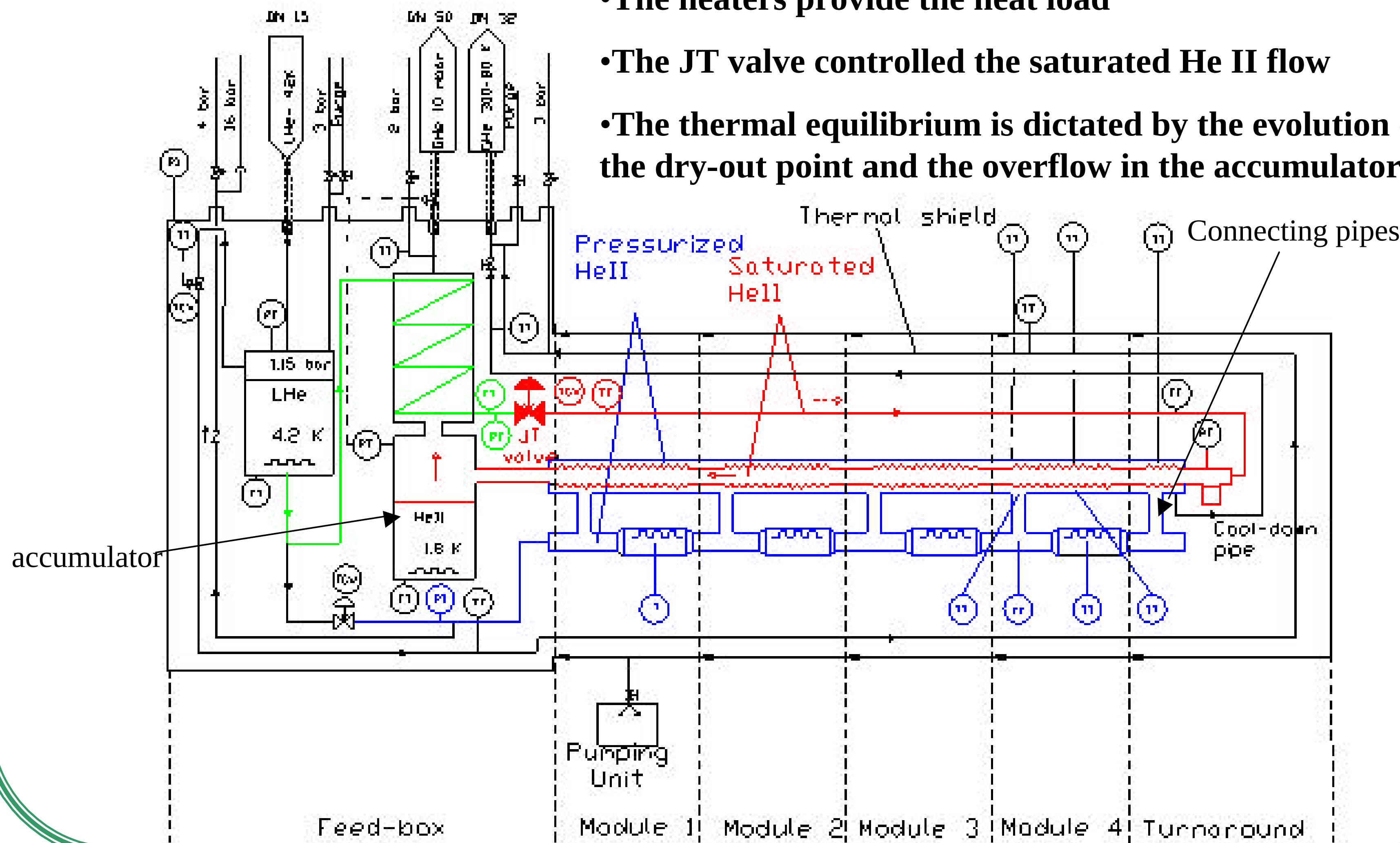
Stainless steel flange

Corrugated tube

Material	**Copper -OFHC**
OD/ ID (mm)	**97/86**
Wall thickness (mm)	**0.7**
Corrugation depth (mm)	**5**
Corrugation pitch (mm)	**12.4**
Surface (cm^2) for one side	**416**
Shape of the corrugated pipe	**Helical**
Surface treatment	**None**

Process and Instrumentation Diagram

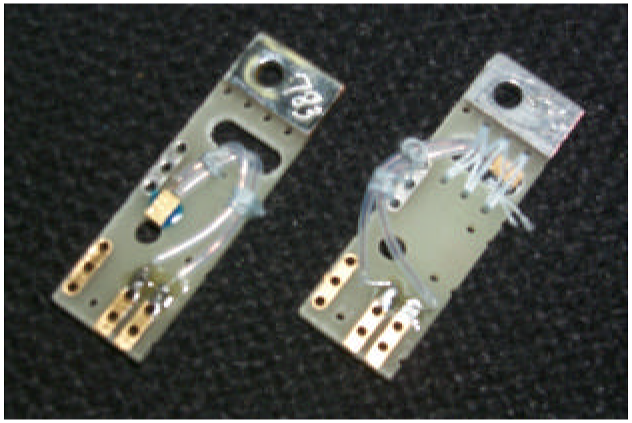
- The heaters provide the heat load
- The JT valve controlled the saturated He II flow
- The thermal equilibrium is dictated by the evolution of the dry-out point and the overflow in the accumulator



Instrumentation

Instrumentation	Total	Range	Accuracy
Temperature (Cernox®, Pt100)	54	1.6 – 40 K, 50 K – 300 K	± 5 mK, ± 5 K
Pressure (Absolute, Differential)	5	0-1.3 bar, 0-0.13 bar, 0-7.5 mbar	0.2%, 0.03 mbar
Level (AMI)	5	0-6”, 0-12”, 0-28”	± 2% FS
Flowmeter (Turbine+RT)	2	0-20 g/s	± 2% FS
Heaters (Electrical resistances)	12	55, 90, 240 Watts	
Control Valves	6	0-100 %	

Temperature sensors implemented in the pressurized He II bath



- Error of +/-5 mK on the temperature measurements.
- Stainless steel tubes to route the wires.

Acquisition and Control system

- ☞ Instrumentation (temperature sensor, pressure transducers, mass-flowmeter, controlled valves…)
- ☞ An industrial PLC acquires and controlled the sensors and valves.
- ☞ Profibus fieldbus routes the information to the acquisition system.
- ☞ PCVue32 is the software used for the graphic interface, controlled and acquisition
- ☞ Ethernet network permits us to acquire and supervise the equipment

Heat transfer in superfluid helium

Gorter-Mellink equation:

$$\frac{dT}{dx} = -f(T)q^m$$

with 1/f(T) = thermal conductivity of He II

Heat flux (W/cm^2)

If T=1.85 K to 1.95 K @ 1 bar

then 1/f(T) = 1200 W^3/cm^{5}K for m=3

$$q = q_0 + \frac{Qx}{A}$$

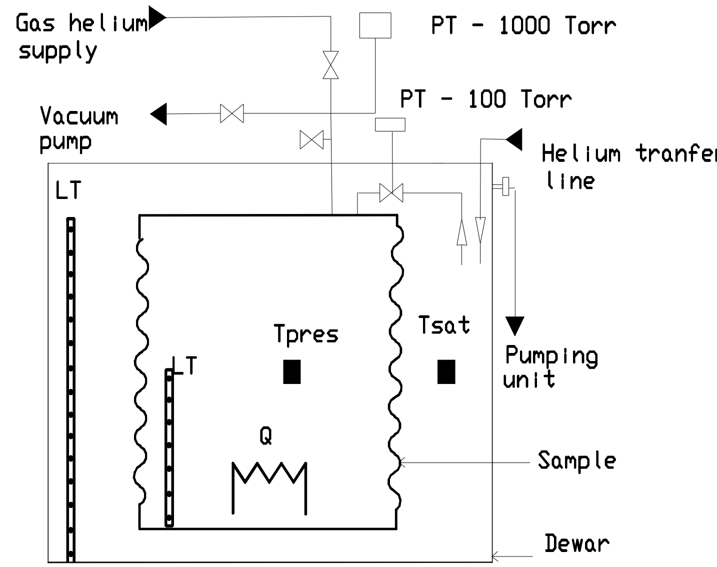
Heat flux through the superfluid into the system

For estimating the temperature difference in regions with distributed heat input, we can use:

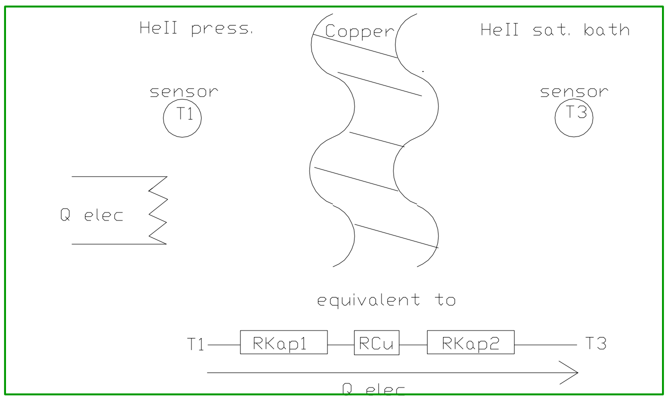
$$\Delta T = \frac{A}{(m+1)Q(1/f(T))}\left(q_L^{\,m+1} - q_0^{\,m+1}\right)$$

Heat transfer and Kapitza Effect

Determination of the Kapitza resistance:
Small scale Heat Exchanger test @ FNAL



$Rth=(Tpres-Tsat)/Qelec$

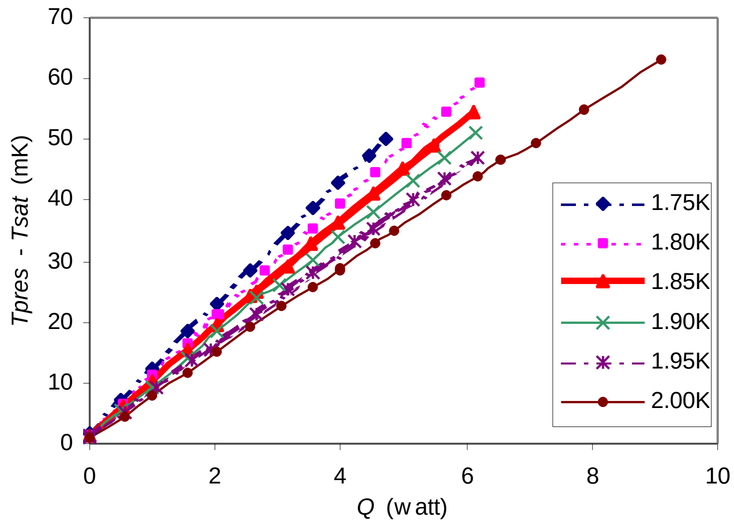


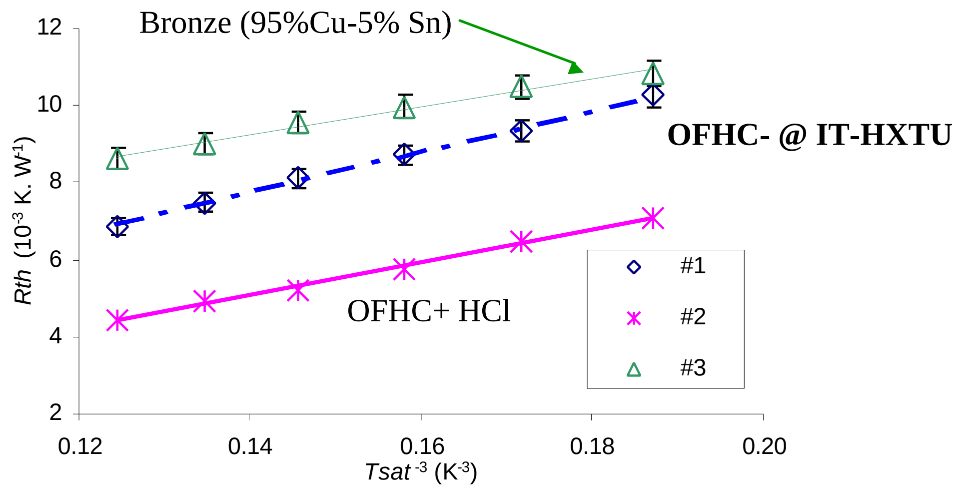
$Rth=2.Rkapitza+Rcu=\alpha(1/Tpres^3)+b$

$$\begin{cases} \alpha = \dfrac{2}{Ckapitza \cdot S} \\ \beta = \dfrac{e}{S \cdot Ccu} \end{cases}$$

Rkapitza

Heat transfer and Kapitza Effect





		#1 - OFHC	#2 – OFHC + HCl	#3 - Bronze
Characteristics				
	OD/ ID (mm)	97/86	97/86	123/101
	Wall thickness (mm)	0.7	0.7	0.5
	Corrugation depth (mm)	5	5	11
	Corrugation pitch (mm)	12.4	12.4	11.7
	Surface (cm^2) for one side	416	416	978
	Shape of the corrugated pipe	Helical	Helical	Bellows
	Surface treatment	None	Hydrochloric acid	None
Results				
	CKapitza ($W \cdot K^{-4} \cdot m^{-2}$)	893	1138	565
	Kapitza conductance @ 1.85 K ($W \cdot K^{-1} \cdot cm^{-2}$)	0.565	0.72	0.357
	Thermal conductivity @ 1.85 K ($W \cdot K^{-1} \cdot m^{-1}$)	88	88	2.4
	Relative performance	Ref.	27%	-37%

Installation & Commissioning of the IT-HXTU

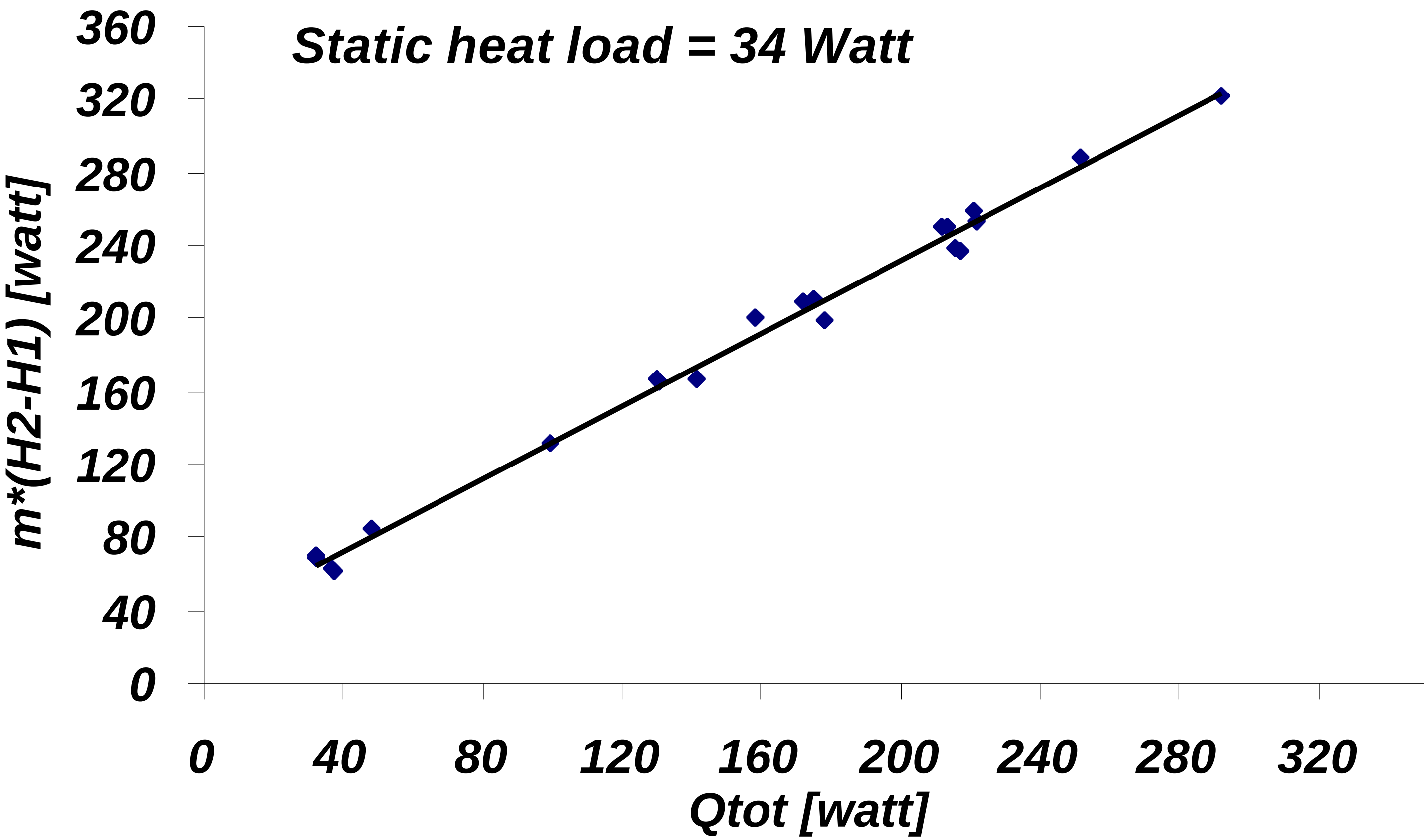
1. Measurement of the heat exchanger tube deflection :< 8 mm
2. Installation on the supports (1.4%)
3. Connecting the 4 modules
4. Pressure test: 2.5 bar abs
5. Leak check: 10^{-8} mbar l/s (@120 mbar)
6. Mechanical calibration of the controlled valves

☞ **At cryogenic temperatures**

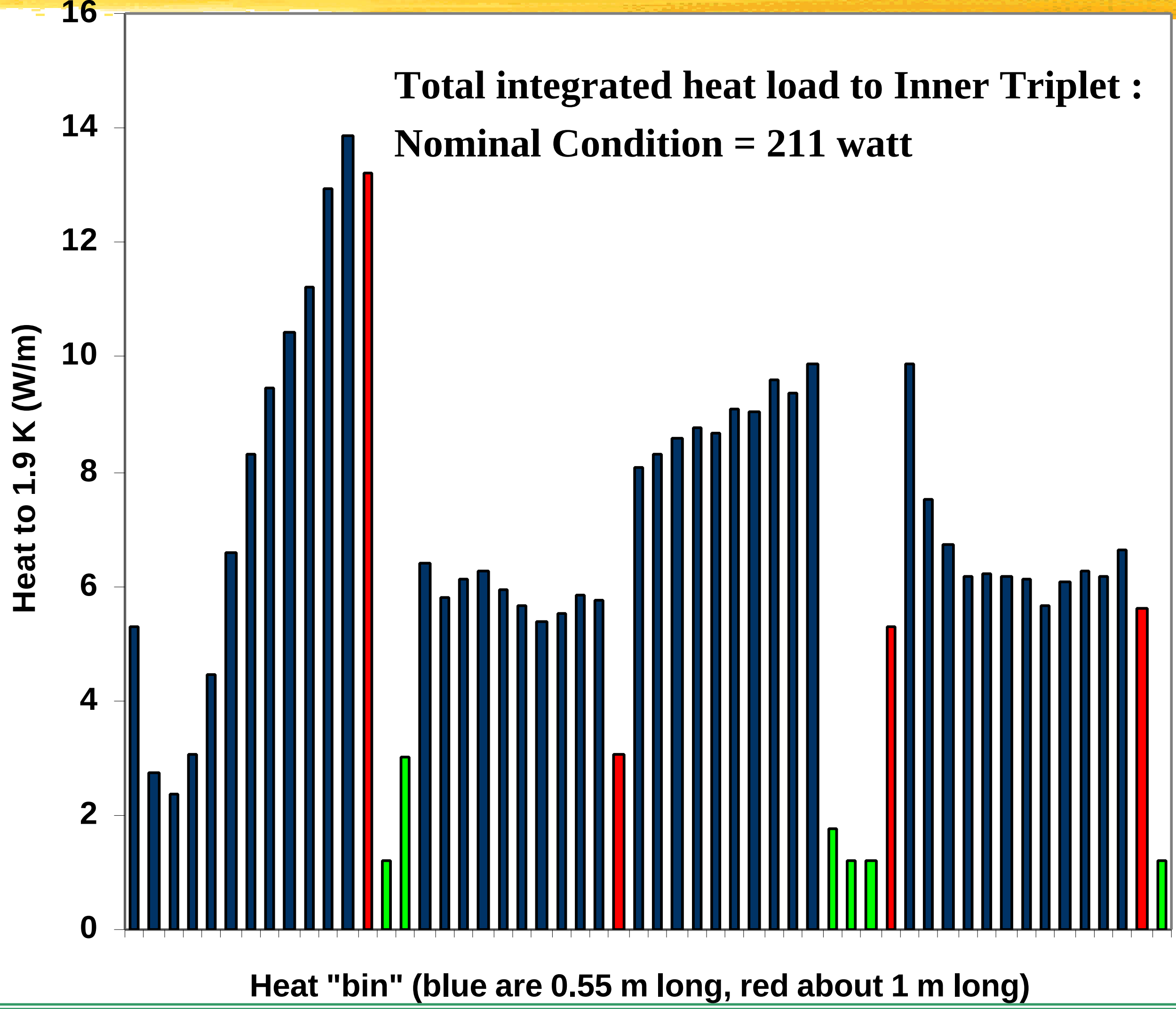
- Time constants for the thermal equilibrium: 4-6 hours
- LHe velocity measurements:10 cm/s
- Controlled valves, JT valve: PID parameters
- Recalibration of thermometers
- Calibration of the turbine mass-flow meter
- Calibration of the JT opening
- Static heat load measurements

Determination of the static heat loads

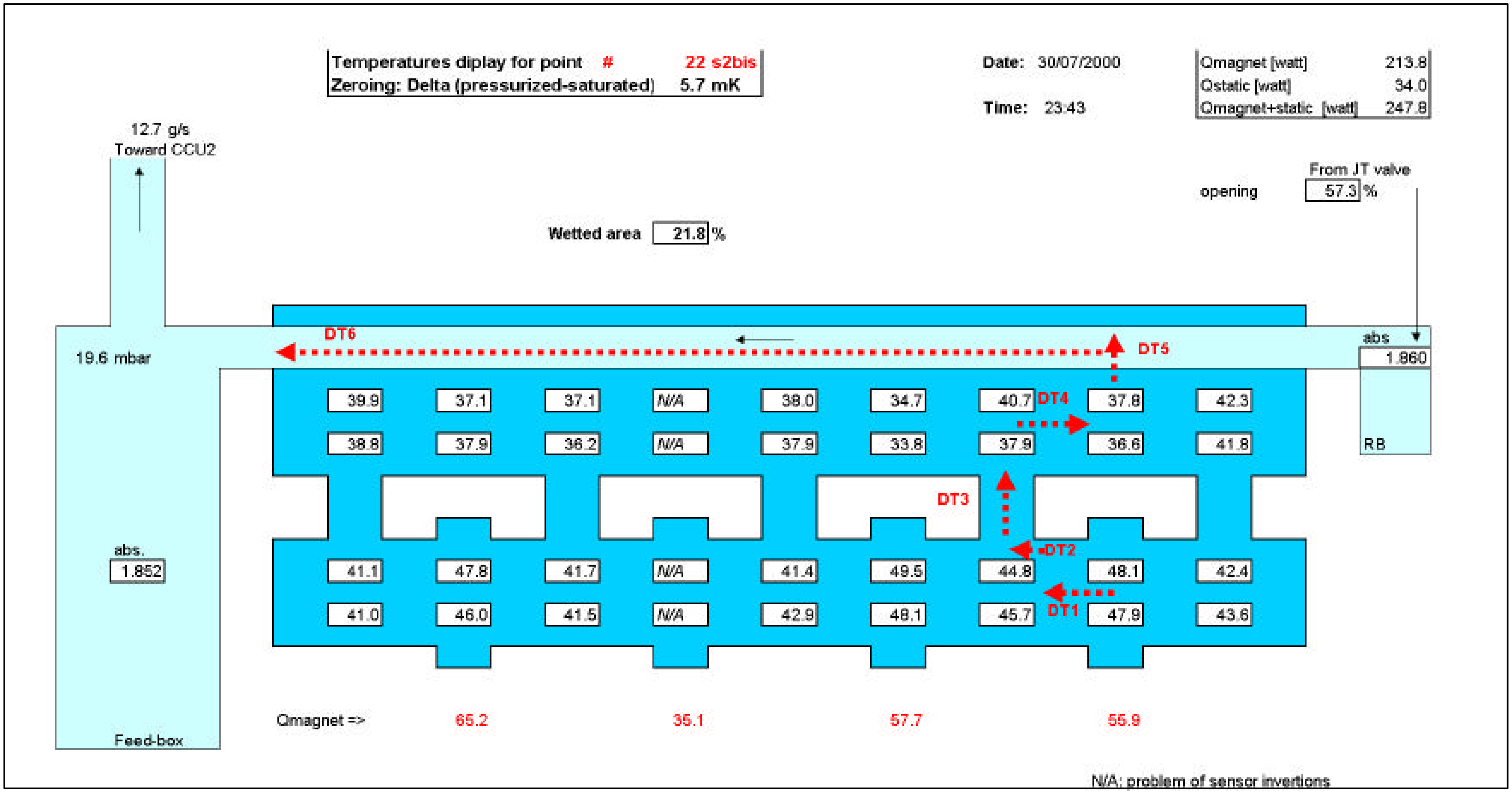
☞The static heat load was measured using the enthalpy balance between the JTvalve and the accumulator



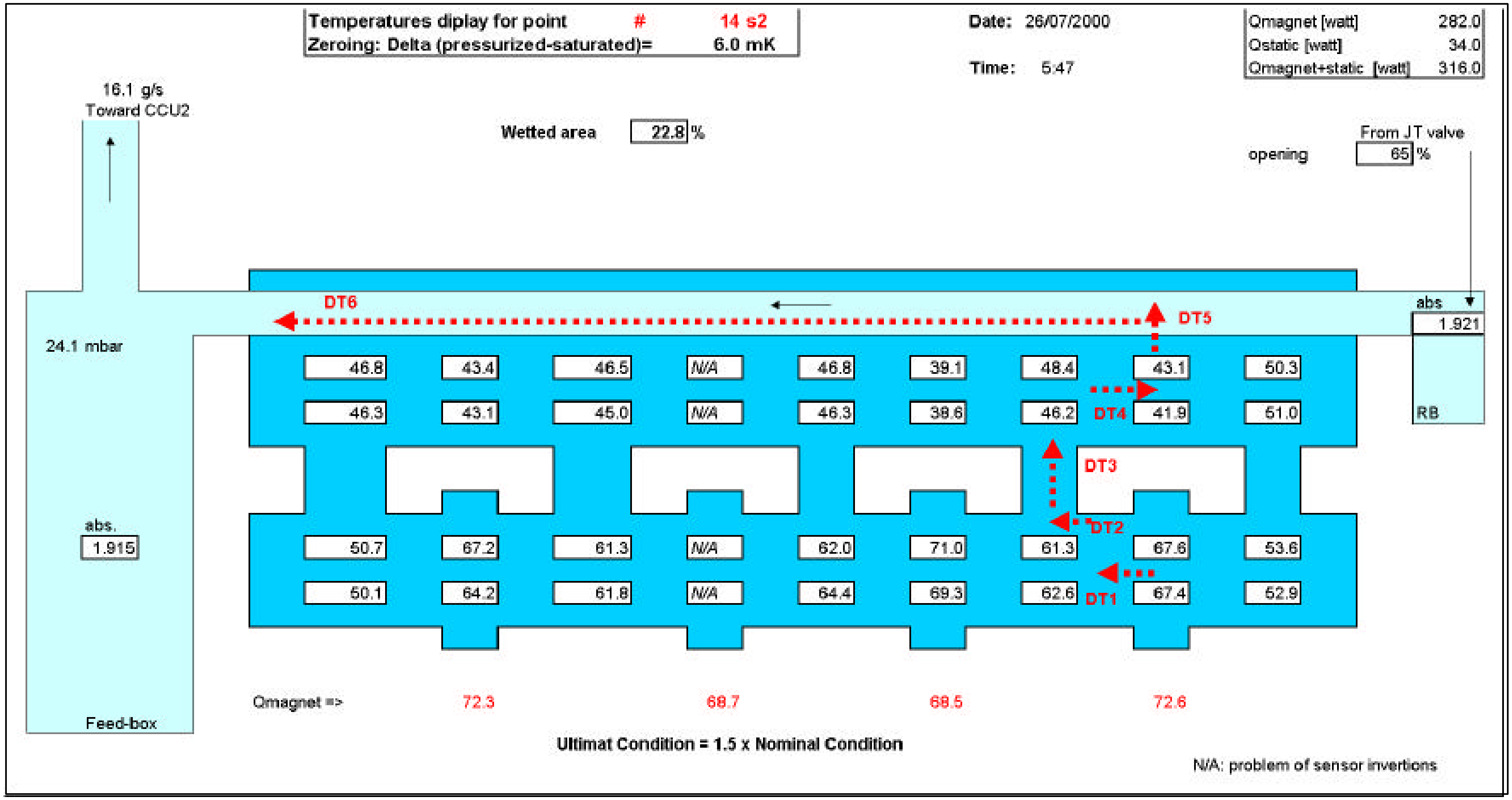
Nominal condition



Nominal condition



IT-HXTU Ultimate condition Q= 315 W



Comparison with calculation

DT1: from the Module 3 thermal center
to the module end within the pressurized Helium II,
linearly increasing heat flux
(length=3.17 m, diameter =13.45 cm)

DT2: within the connecting pipe between modules
within the pressurized Helium II, constant heat flux
(length=40 cm, diameter=8.28 cm)

DT3: between connecting pipe and heat exchanger
within the pressurized Helium II, constant heat flux
(length=7.2 cm, diameter=8.28 cm)

DT4: within the pressurized Helium II side of
the heat exchanger, linearly decreasing heat flux
L=375 cm, D_inner=9.6 cm, D_outer=16 cm.

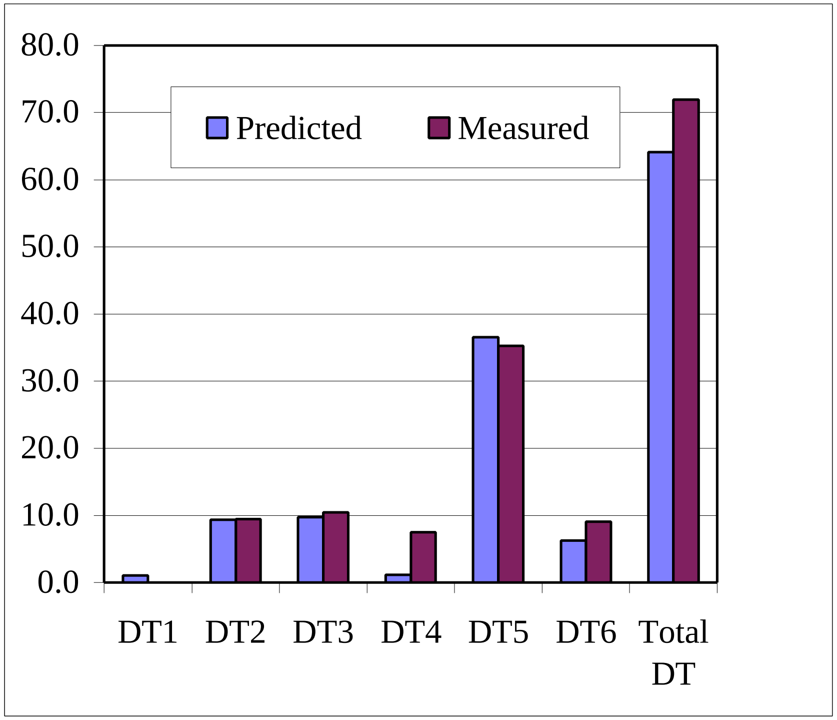
DT5: across the He II heat exchanger wall

DT6: due to the vapor pressure drop.

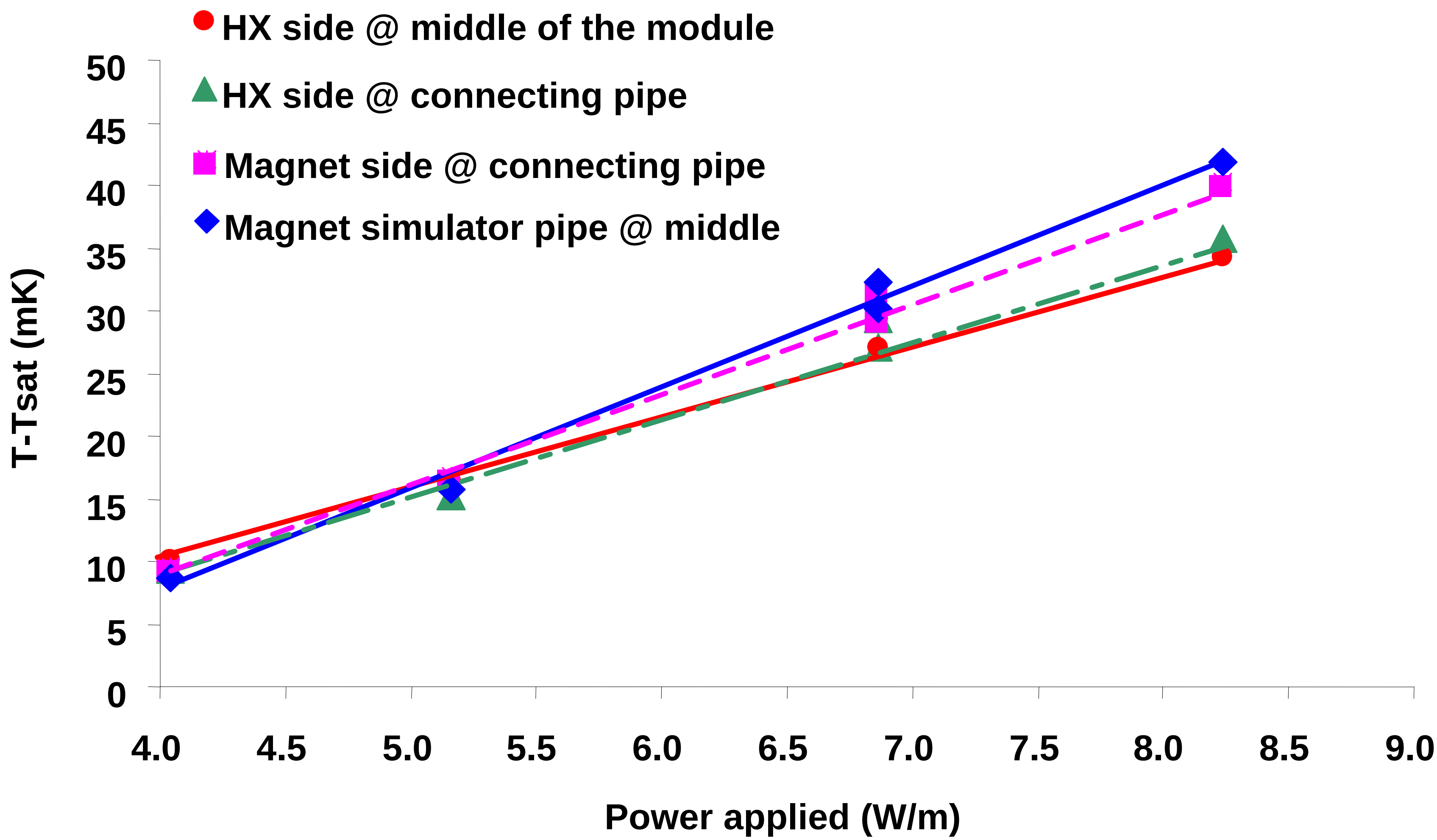
	Module 4	3	2	1
Electric power (W) =	73.13	72.54	47.19	85.90

Total electric plus static heat = 312.8 Watts

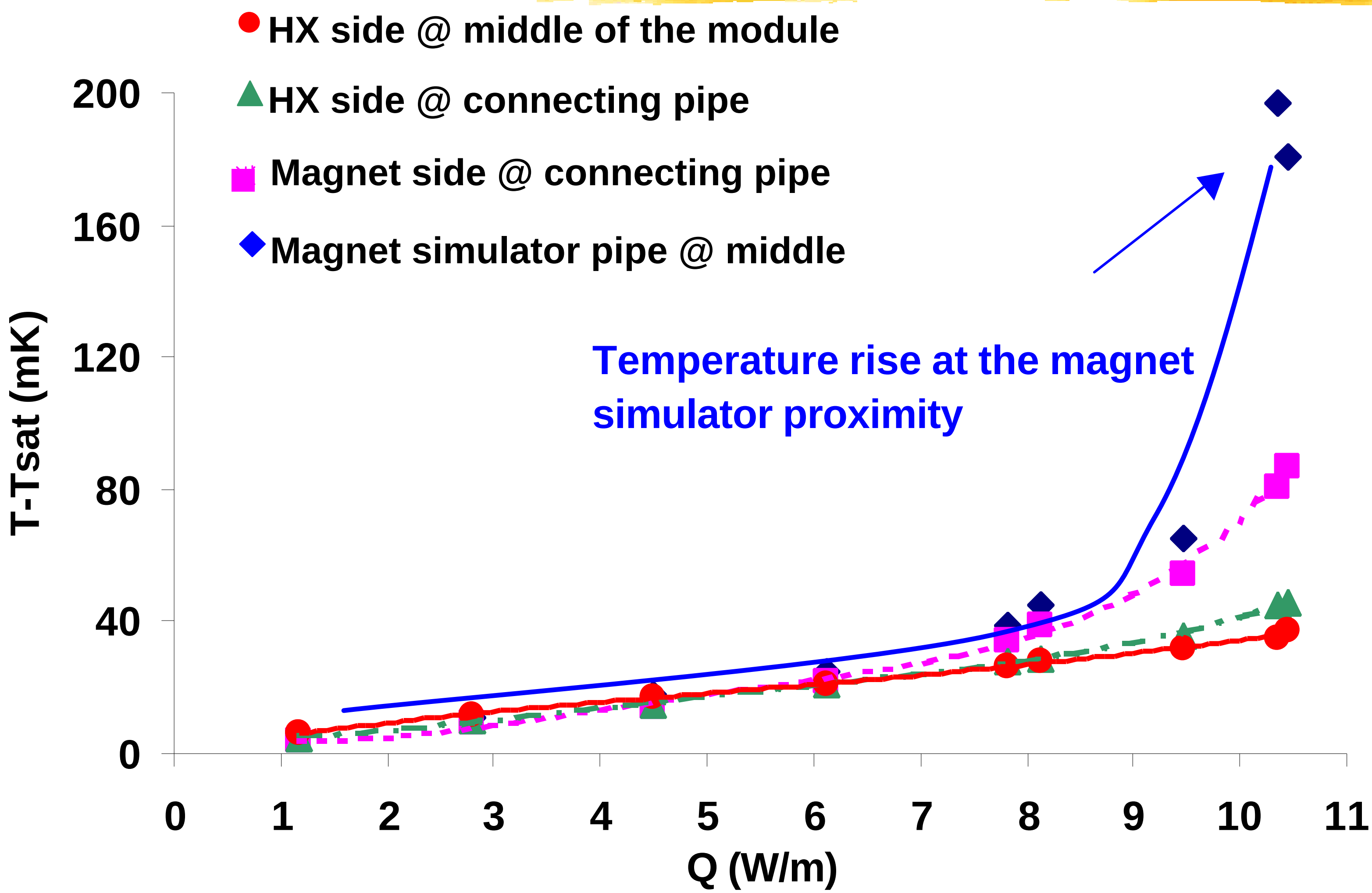
Tsat (K) = 1.921 Average heat = 10.43 W/m



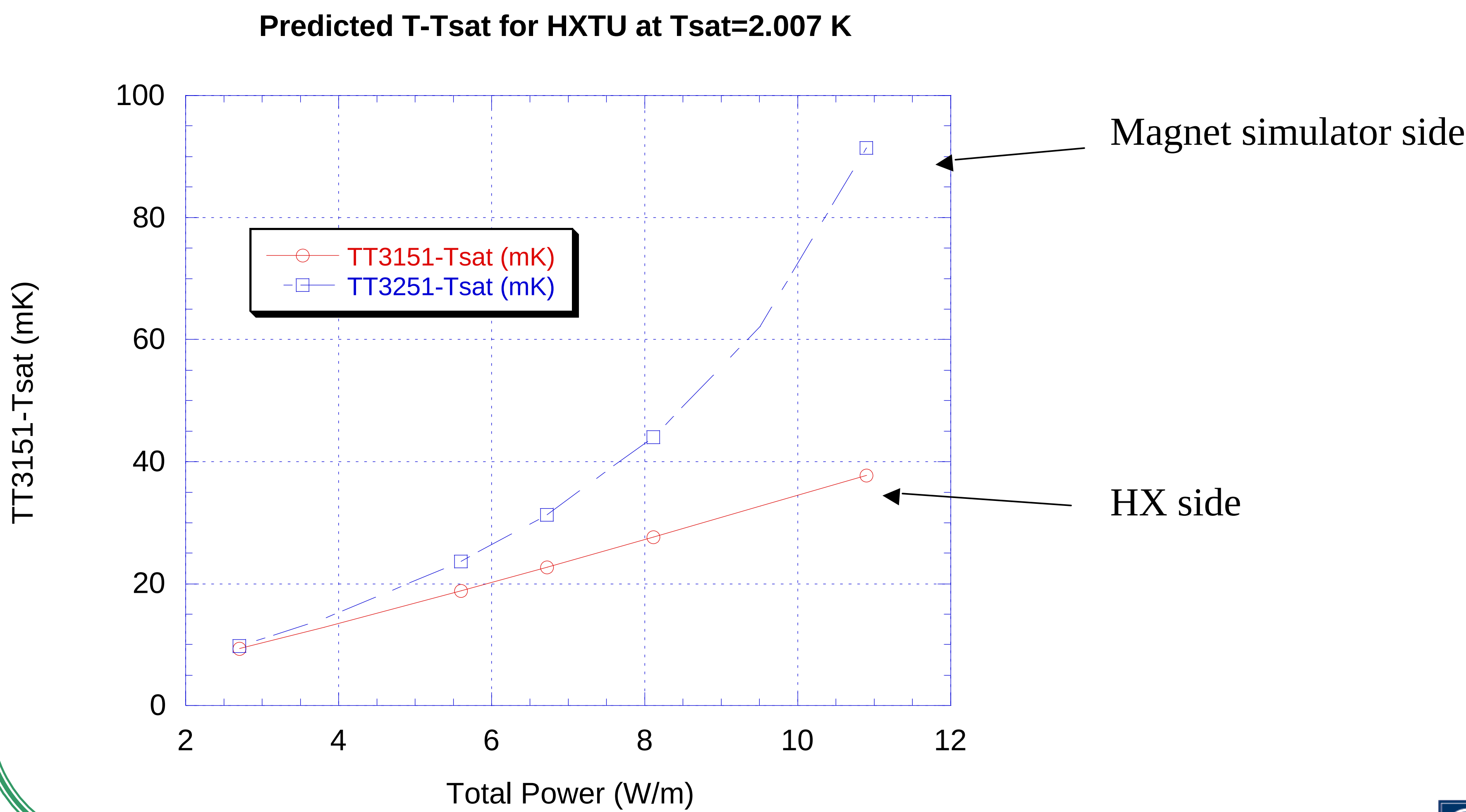
DT vs. heat load - Tsat ~ 1.90 K ~21 mbar



DT vs. heat load - Tsat ~ 2.00 K ~32 mbar



Prediction for LHC high luminosity conditions



Conclusions

☞ **More than 50 heat load configurations were measured**
http://tspc01.fnal.gov/darve/heat_exchanger/instrumentation.html

☞ **Validation of the theoretical model**

☞ **The temperature rise at nominal LHC luminosity conditions will not exceed 50 mK.**

☞ **The wetted area of the heat exchanger tube is about 22 %.**

☞ **Increase of the connecting pipe diameter in order to reduce the temperature rise resulting from the potential LHC ultimate luminosity condition.**

Acknowledgement

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